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Numerical simulation of THz emission from two mesa-structured intrinsic Josephson junctions

H. Asai[a]*, M. Tachiki[a], H. Minami[a], T. Yamamoto[b], K. Kadowaki[a]

[a] *Faculty of Pure and Applied Science, Division of Material Science, University of Tsukuba, Ten-noudai 1-1-1, Tsukuba, Ibaraki 305-8573, Japan*

[b] *Takasaki Advanced Radiation Research Institute,Japan Atomic Energy Agency,1233 Watanuki, Takasaki, Gunma 370-1292, Japan*

Abstract

In this study, we have numerically investigated the radiation from two separated mesa-structured intrinsic Josephson junctions (IJJs) which are electrically connected in series. We have calculated electromagnetic field inside and outside of IJJs simultaneously using two dimensional model. The radiation power has been calculated as a function of the distance between two mesas. We have observed the oscillation of the radiation power with respect to the distance coming from the change of electromagnetic interaction between the mesas. In particular, at the distances where the electromagnetic standing waves appear in the interspace between the mesas, the radiation powers become larger than twice the power emitted by one isolated mesa. We have also calculated the radiation patterns emitted by two mesas and found that the radiation patterns greatly change with the distances.

Keywords: intrinsic Josephson junctions; THz emission; mesa array

1. Introduction

Recently, the radiation of coherent THz waves from high Tc superconductor $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO) single crystal has been reported [1–4]. In BSCCO samples, ac Josephson currents fl w under dc bias voltages between intrinsic Josephson junctions (IJJs) which consists of stacking of superconducting CuO_2 layers and insulating Bi-Sr-O layers. The intense radiation has been reported in both experimental and theoretical studies under the voltages where the *ac* Josephson frequencies coincide with cavity resonant frequencies of the BSCCO mesa [1–8]. To achieve high power THz emission, the radiation from a number of electrically connected BSCCO mesas has attracted much attention in recent years. Orita et al., have investigated the intensity of radiation from two serially connected mesas and reported the increase of total radiation power suggesting synchronized operation of these mesas [9]. However, the mechanism of the increase of radiation power has not been clarifie yet.

In this paper, we present the numerical simulation of the radiation from two separated mesa-structured IJJs which are electrically connected in series. We have calculated the electromagnetic field inside and

*Corresponding author. Tel.: +81 (0)29 853 8802; Fax: +81 (0)29 853 8802.
Email address: hide@ims.tsukuba.ac.jp. (H. Asai[a])

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outside of IJJs simultaneously using two dimensional model. To clarify the arrangement in which the radiation power increases, we have calculated the radiation power as a function of the distance between the two mesas. The radiation power oscillates with respect to the distance due to the change of electromagnetic interaction between the mesas. In particular, at the distances where the electromagnetic standing waves appear in the interspace between the mesas, the radiation power becomes larger than twice the power emitted by one isolated mesa. We have also calculated the radiation patterns emitted by two mesas for several distances and found that the radiation patterns greatly change with the distances.

2. Calculation Method

In this study, we consider two dimensional slice (x-z plane) of infinit long mesa samples whose IJJs stack along the z axis. Figure 1 shows the schematic figur of our calculation model. The two mesas are sandwiched by infinit size substrates and upper electrodes. The widths of the electrodes are the same as those of the mesas. We assume the substrate and electrodes are perfect electric conductors. The *dc* external current is injected from the right upper electrode and fl w through the two mesas and the substrate to the left upper electrode. The dotted arrows indicate the path of the *dc* current. For the outer boundary of the system, we use the perfectly matched layer absorbing boundary condition. The geometries of the two mesas are same, and the sizes are as follows: width $w = 0.48\lambda_c$, height $h = 0.02\lambda_c$, where λ_c is the penetration depth along the IJJ plane.

We use in-phase approximation: all phase differences between IJJ layes are equal to each other. In this approximation, time evolution of non dimensional electromagnetic field and the phase differences in the IJJs are described by the following equations[8, 10]

$$\frac{\partial}{\partial t'}P = E'_z, \quad B'_y = \frac{\partial}{\partial x'}P, \quad \frac{\partial}{\partial t'}E'_z = \frac{1}{\epsilon_c}\frac{\partial}{\partial x'}B'_y \pm j'_{ext} - \sin P - \beta E'_z,$$

where, P is the phase difference between IJJs, E_z is electric field B_y is oscillating part of magnetic field and j_{ext} is the *dc* external current uniformly injected into IJJs. The sign of the external current is plus for left mesa (mesa I) and minus for right mesa (mesa II). The parameter $\beta = 4\pi\lambda_c\sigma_c/c\sqrt{\epsilon_c}$ is normalized conductivity and ϵ_c is the dielectric constant of the junctions. In this study, we take $\epsilon_c = 16$, $\beta = 0.075$. In the above equations, we use non dimensional quantities as follows: length $x' = x/\sqrt{\epsilon_c}\lambda_c$, time $t' = \omega_p t$ where $\omega_p = c/\sqrt{\epsilon_c}\lambda_c$, electromagnetic fiel $E' = (2eD/\hbar\omega_p)E$, $B' = (2eD/\hbar\omega_p)B$ where D is the thickness of insulating layers of IJJs, and current $j' = (8\pi^2 D\lambda_c^2/c\phi)j$. In the outside region of the IJJs, we solve the two dimensional Maxwell's equation.

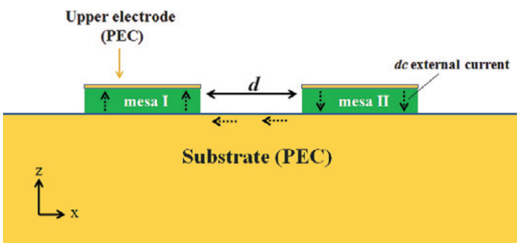

Fig. 1. A schematic view of two dimensional calculation model.

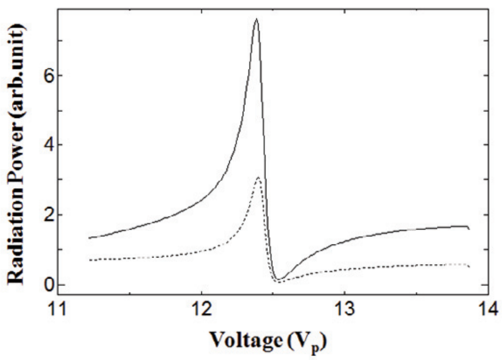

Fig. 2. The radiation power as a function of voltage at $d = 1.24\lambda_0$.

3. Results and discussions

To investigate the dependence of the radiation power on the arrangements of the mesas, we have calculated the radiation power with changing the distance d between the two mesas. As reported in previous theoretical studies [6, 8], the homogeneous mesa-structured IJJs in the in-phase mode shows strong emission at the voltages where the *ac* Josephson frequency $f_J = 2eV/h$ satisfie the even-numbered cavity resonance condition $f_J = cn/2\sqrt{\epsilon_c}w$, where n is even number. In this study, we have focused on the strong emission in the condition $n = 2$. For various values of d, we have calculated the radiation power as a function of voltage around this condition. Then, we have estimated the maximum radiation power for each d. Figure 2 shows the example of the radiation power versus voltage curve at $d = 1.24\lambda_0$. Here, voltage is normalized by $V_p = \hbar\omega_p/2e$, and λ_0 is the wavelength of the radiation wave in free space. The dotted line indicates the radiation power emitted by one isolated mesa. We can see the sharp peaks of the radiation around $V = 12.4V_p$ where f_J satisfie cavity resonance condition $n = 2$. In Fig. 3, we plot the maxmum radiation power as a function of d. Here, P_0 is the maximum radiation power emitted by one isolated mesa. As shown in this figure the radiation power oscillate with respect to d, and the period of the oscillation is about λ_0.

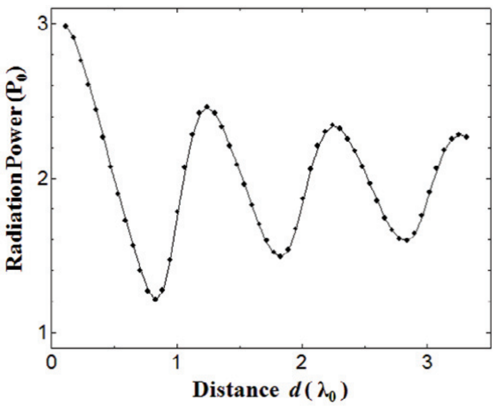

Fig. 3. The radiation power as a function of d.

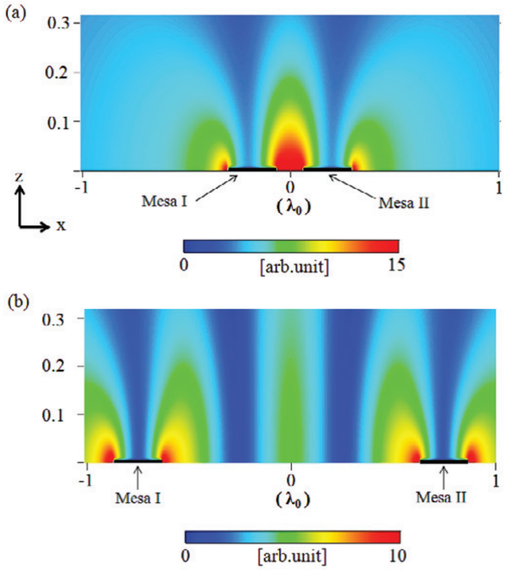

Fig. 4. The amplitude map of the H_y oscillating at *ac* Josephson frequency for (a) $d = 0.12\lambda_0$ and (b) $d = 1.24\lambda_0$.

This oscillation can be understood from the change of the electromagnetic interaction between the mesas. In this system, the phase of magnetic fiel H_y near the right edge of the mesa I and the left edge fo the mesa II are equal. Hence, when the d is small, the oscillation of H_y between the mesas is enhanced by constructive interference. In Fig 4 (a), we show the amplitude map of H_y oscillating at *ac* Josephson frequency in the case of $d = 0.12\lambda_0$. To make the radiation fiel clear, the fiel inside the mesas is not shown here. In this figure we can see the large oscillation of H_y in the interspace between the mesas. The large oscillation of magnetic fiel near the mesa edge induces the oscillating current fl wing through the mesa and enhances the Josephson plasma excitation in the IJJs. In consequence, the radiation power emitted by each mesa increases, and the total radiation power become larger than $2P_0$. Moreover, the enhancement of the radiation power also occur around $d = n\lambda_0 + 0.24\lambda_0$, where n is an integer. In Fig 4 (b), we show the amplitude map of H_y oscillating at *ac* Josephson frequency in the case of $d = 1.24\lambda_0$. As shown in these figures the standing wave of H_y whose antinodes are located at the mesa edges appear in the interspace of the two mesas. Similar to the above, the large oscillation of magnetic fiel near the mesa edge enhances the radiation power. Meanwhile, when d is far from the above conditions, oscillating field H_y at mesa edges are suppressed by the destructive interference. Then, the radiation power emitted by each mesa decreases, and the total radiation power become smaller than $2P_0$.

In this manner, the radiation power varies with a period of λ_0 due to the change of electromagnetic interaction between the mesas. This interaction becomes weak with increasing distances, hence the amplitude of the power oscillation become small for large d as shown in Fig 3. It should be noted that the distance d where the standing waves appear is $0.24\lambda_0$ larger than integral multiple of λ_0. This deviation from $d = n\lambda_0$ is considered to come from the decrease of effective distance by the existence of fringing fiel at the mesa edges. Finally, in Fig 5, we show the radiation pattern emitted by the two mesas for $d = 0.84\lambda_0$ and $d = 1.24\lambda_0$. As shown in this figure the radiation pattern at $d = 1.24\lambda_0$ where the mesas show strong emission differ substantially from the pattern at $d = 0.84\lambda_0$ where the mesas show weak emission. Therefore, the analyses of the radiation patterns could be helpful to understand the details of electromagnetic interaction between the mesas.

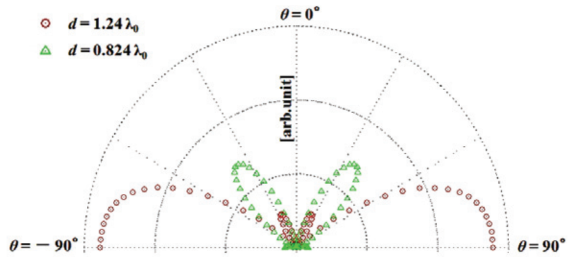

Fig. 5. The polar plots of radiation intensity emitted by the two mesas at $d = 0.84\lambda_0$ and $d = 1.24\lambda_0$.

4. Conclusion

In this study, we have numerically investigated the radiation from two separated mesa-structured intrinsic Josephson junctions (IJJs) which are electrically connected in series. We have calculated the radiation power as a function of the distance between two mesas. We have observed the oscillation of the radiation power with respect to the distance coming from the change of electromagnetic interaction between the mesas. In particular, at the distances where the electromagnetic standing waves appear in the interspace between the mesas, the radiation powers become larger than twice the power from one isolated mesa. We have also calculated the radiation patterns emitted by two mesas and found that the radiation patterns greatly change with the distances. Our results indicate that the control of the arrangement of the IJJs array is one of key factors to design high power IJJs array.

Acknowledgements

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